Role of plasma turbulence in collisionless plasmas; what will be learnt from Cross-Scale

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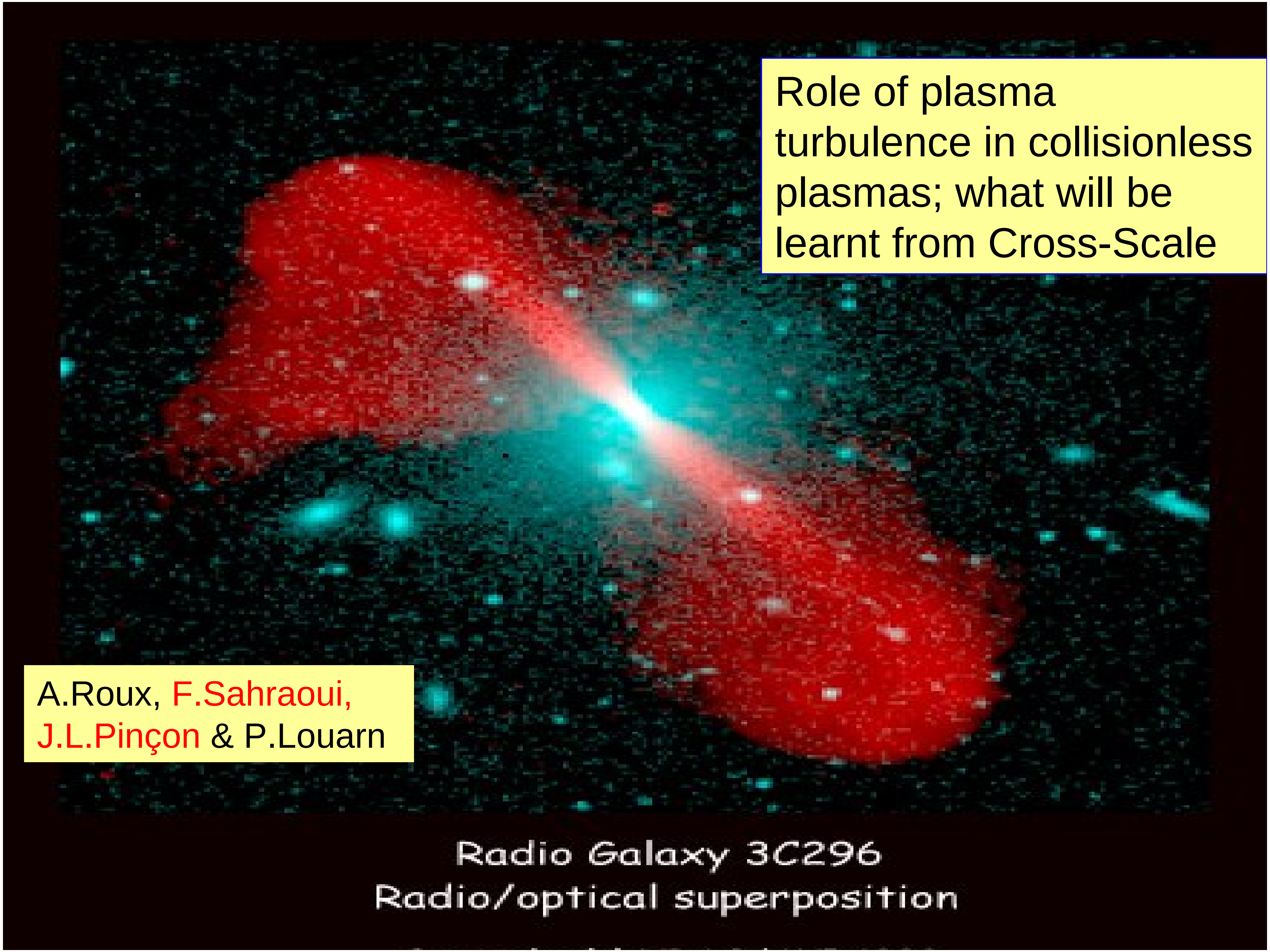


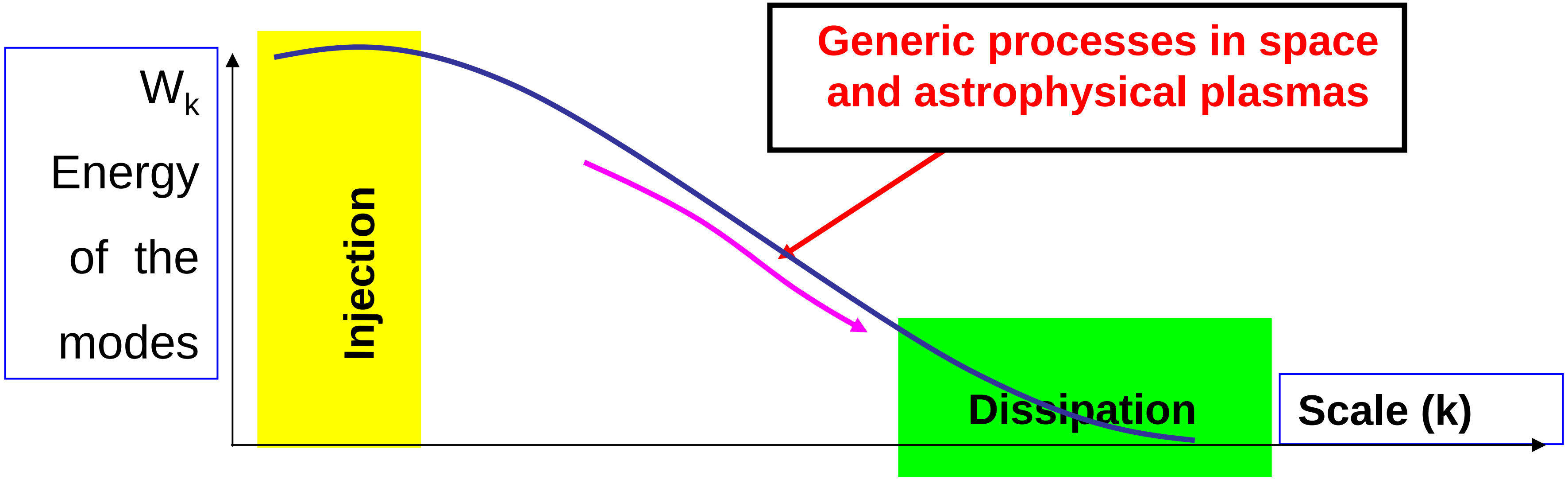
Radio Galaxy 3C296
Radio/optical superposition

Introduction 1. Why study plasma turbulence?

- Plasma turbulence is pervasive in many astrophysical objects: galactic jets, solar corona, SW, accretion disks, planetary environments …, as well as in plasma laboratory devices, such as Tokamaks.
- From the large scale to the sub-electron gyroscale.
- Dynamically important (particle acceler. and transport).
- Fundamental limitation: need for (i) in situ measurements with (ii) proper spatial coverage.
- Cross-Scale offers a comprehensive approach to studying plasma turbulence, via in situ measurements with a sufficient spatial coverage, by means of non destructive measurements.

Introduction 2. Basic properties of turbulence

- Stationnary spectra of the energy (or other invariants), for fields & particles =>scale of the processes by which the energy (or other invariants) is (i) injected, (ii) transferred, and finally (iii) dissipated.



W_k Energy of the modes

Injection

Generic processes in space and astrophysical plasmas

Dissipation

Scale (k)

• In the hot and dilute plasmas met in distant objects as well as in planetary magnetospheres or fusion machines collisions are too rare to produce dissipation. So what does it, and is there a turbulent cascade???

Specificities of collisionless plasmas

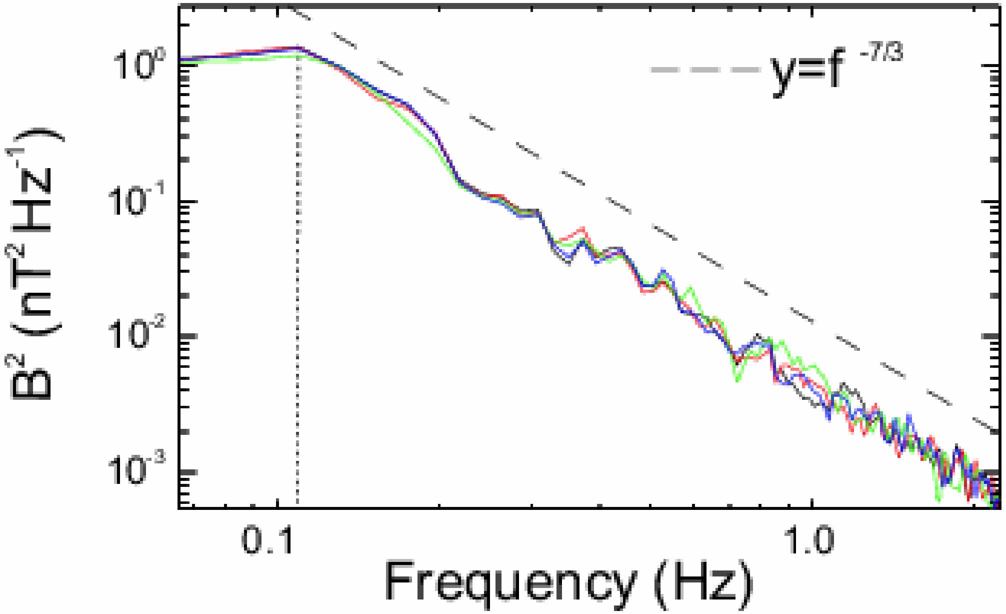
- Unlike fluids collisionless plasmas are not scale invariants.
- Different physical processes take place at different scales.
- Collisionless dissipation, due to phase mixing, can be produced via Landau, cyclotron damping, bounce resonance…which have different scales; sometimes small (Ri), very small (Re), and even very large (Lfield line).
- Collisionless dissipation not described by MHD, unless empirical coefficients are used.
- Unlike fluids eigen modes exist ⇔weak (weak/strong)

Analyses of turbulent spectra

Turbulence theories predict spatial spectra

- ✓ Ko41 ($k^{-5/3}$); IKr ($k^{-3/2}$)
- ✓ Incompressible anisotropic MHD: $k_\perp^{-2}$ (Galtier et al.,2000)
- ✓ Whistler turbul. $k^{-7/3}$ (Biskamp, 97)

But measurements provide only temporal spectra, here $B^2 \sim \omega_{sc}^{-7/3}$



How to infer the **spatial spectrum** from the **temporal one** measured in the spacecraft frame (Doppler shift)? $B^2 \sim \omega_{sc}^{-7/3} \Rightarrow B^2 \sim k_{//}^{?};\ k_\perp^{?}$

Case of the solar wind

In the solar wind : the **Taylor's hypothesis** is valid

Fast plasma velocity (v >> v_φ) ⇒ Doppler shift is **dominant**

$$\omega_{spacecraft} = \omega_{plasma} + \mathbf{k.V} \approx \mathbf{k.V} = k_V V$$

⇒The calculation of a k spectrum is possible with one spacecraft (see f.i. Matthaeus & Goldstein)

But *only* along one single direction

Turbulence in the solar wind : **[HEOS data in SW (Tu and Marsch, 1995)]**

$k^{-5/3}$ **law**

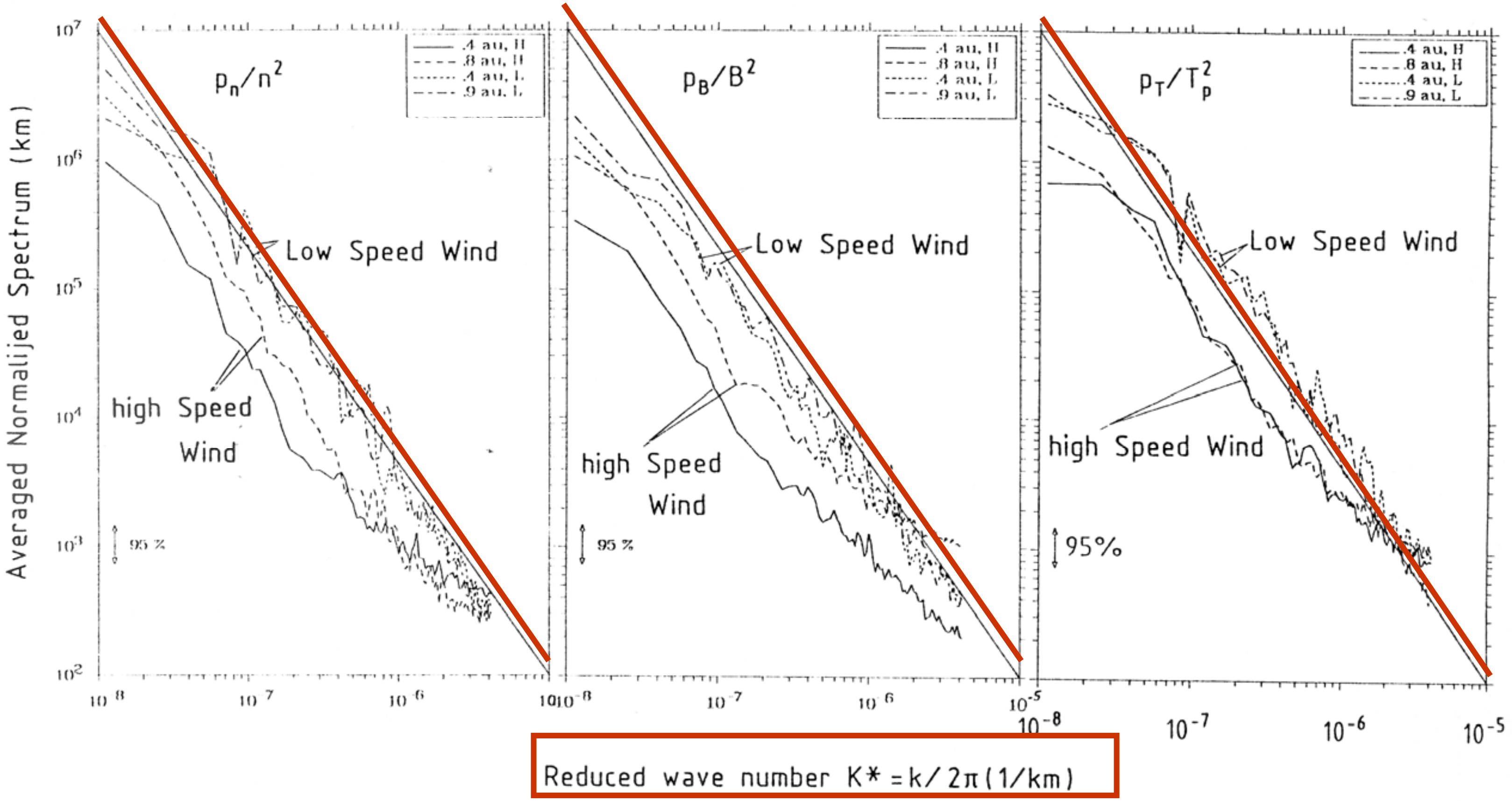
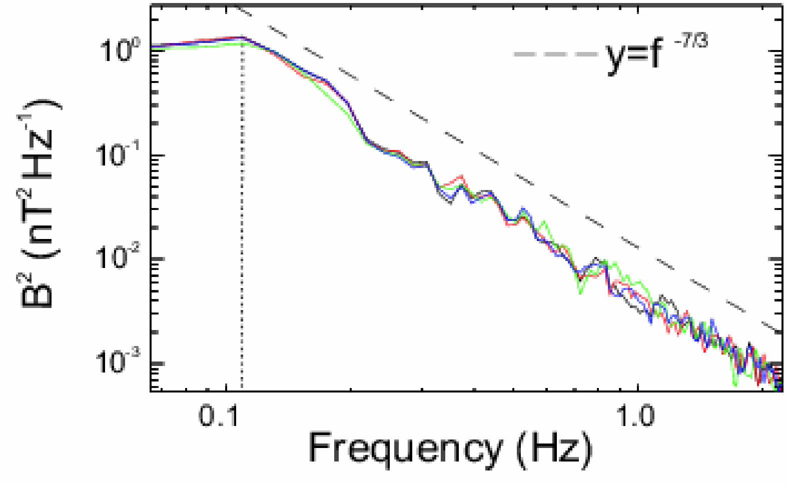


Fig. 2-12. Averaged spectra of relative fluctuations of proton density ($\delta n/n$), magnetic magnitude ($\delta B/B$) and proton temperature ($\delta T/T$) shown from the left to the right respectively. For each variable four average spectra are presented, respectively, for high-speed wind near 0.4 AU (solid line) and 0.8 AU (long-dashed line), and for low-speed wind at about 0.4 AU (short-dashed line) and 0.8 AU (dash-dot line). Each spectrum represents a 48-hours period of data. The single error bars shown in the figure only represent the largest confidence interval, which is calculated for 60 degrees of freedom. The straight line refers to a Kolmogorov $-5/3$ spectrum for comparison (adopted from Marsch and Tu, 1990b, and Tu *et al.*, 1991).

In the magnetosheath

Phase velocities of the modes ~ plasma velocity ~ 200km/s

⇒ **Taylor's hypothesis is useless**



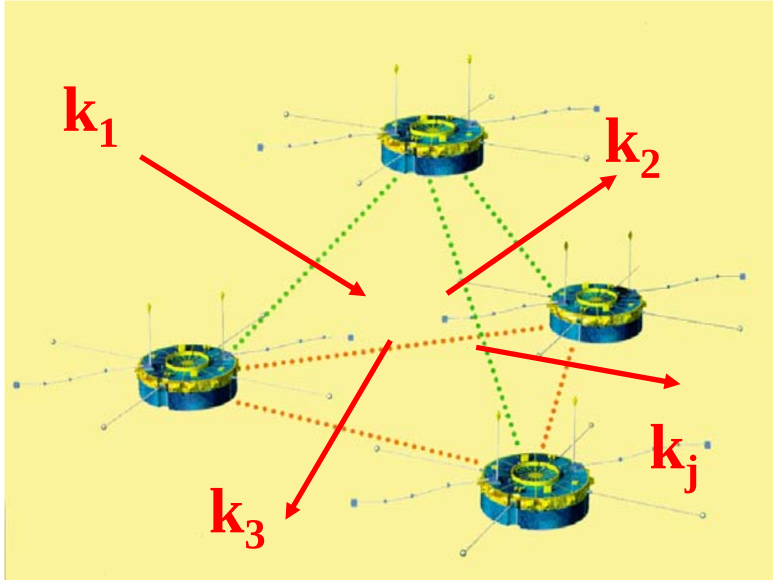
⇒ Inferring the ***k* spectrum** from an ω **spectrum is impossible**

⇒ ***Need for multi-spacecraft measurements and appropriate methods***

Cluster data and the k-filtering (also called wave telescope) technique

Based upon a NL filter bank approach.

Provides an optimized estimate of the spectral energy density $P(\omega,k)$, from simultaneous multipoints measurements

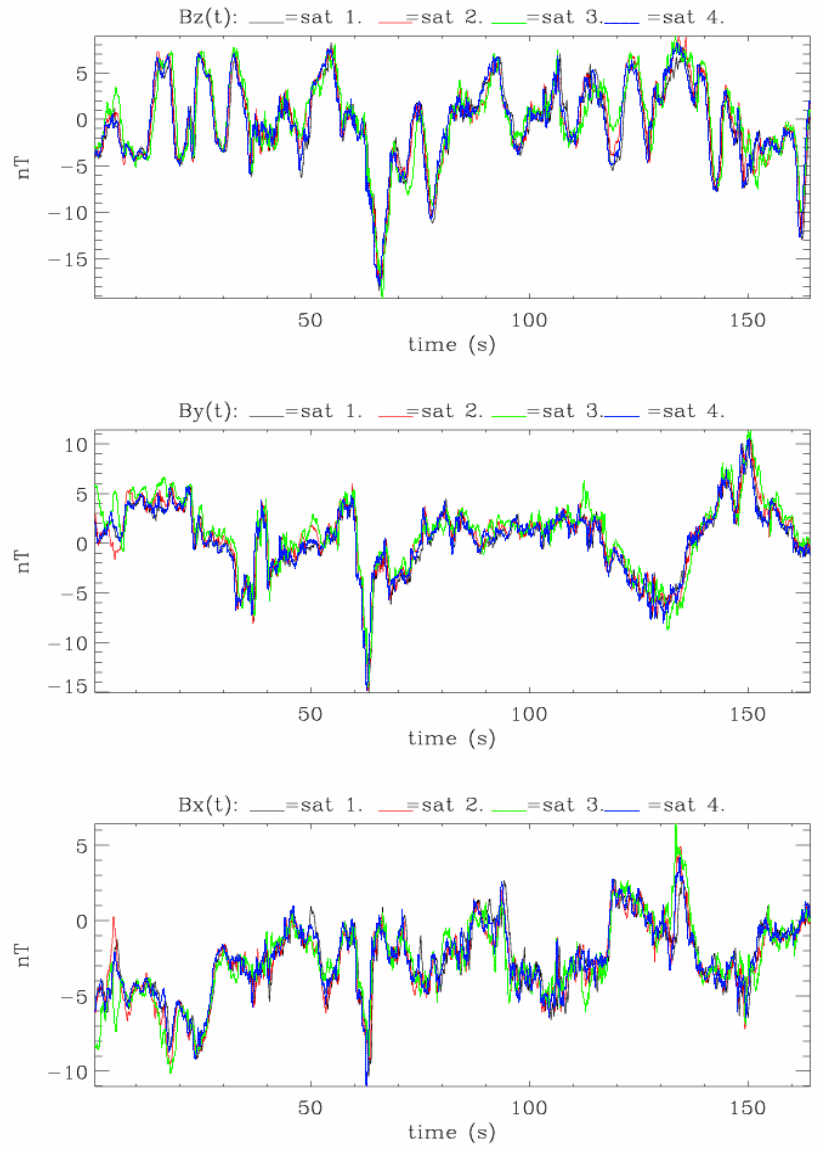


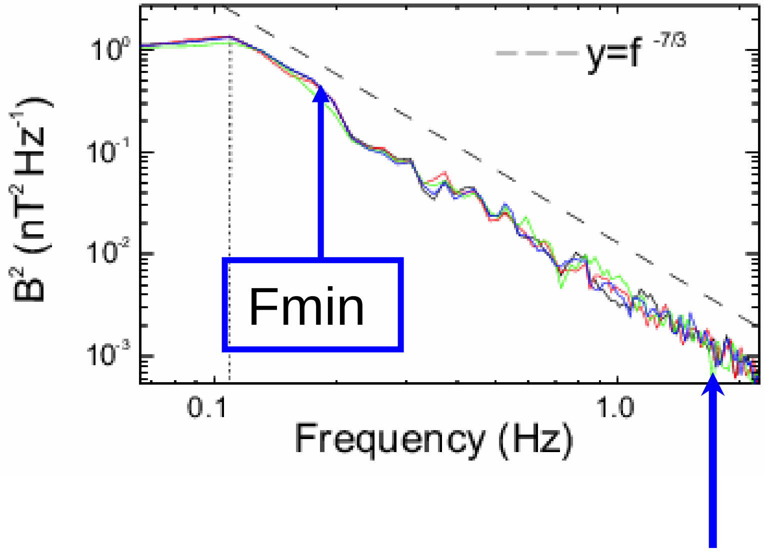
- Uses the global correlation matrix (12 x 12)
- takes into account available theoretical constraints: $\nabla.\mathbf{B}=0$

  (Pinçon & Lefeuvre, 1991; Sahraoui et al., 2003, 2004; Glassmeir et al…)

Cluster data in the magnetosheath

FGM data (18-02-2002, 5:34:00)





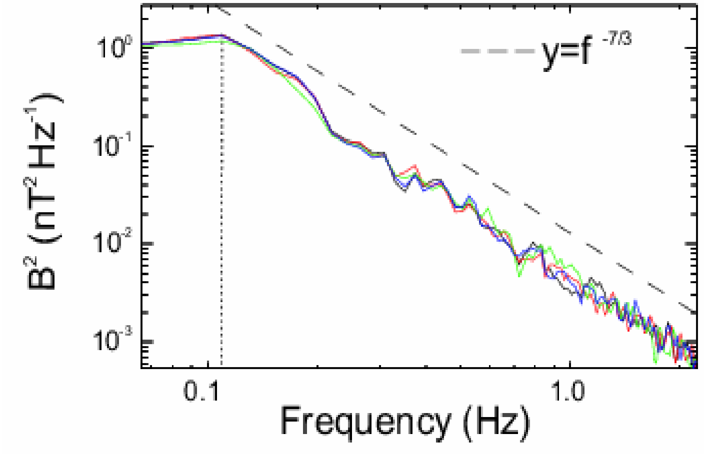
Limit imposed by the Cluster minimum separation ***d~100 km*** :

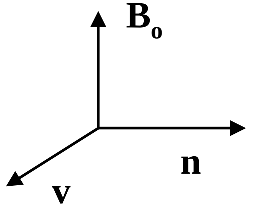
$\omega_{max} \sim k_{max} v_\varphi \sim 2\pi\, v_\varphi / \lambda_{min} \sim 2\pi\, v_\varphi / d$

In the magnetosheath: $v_\varphi \sim 200$ km/s

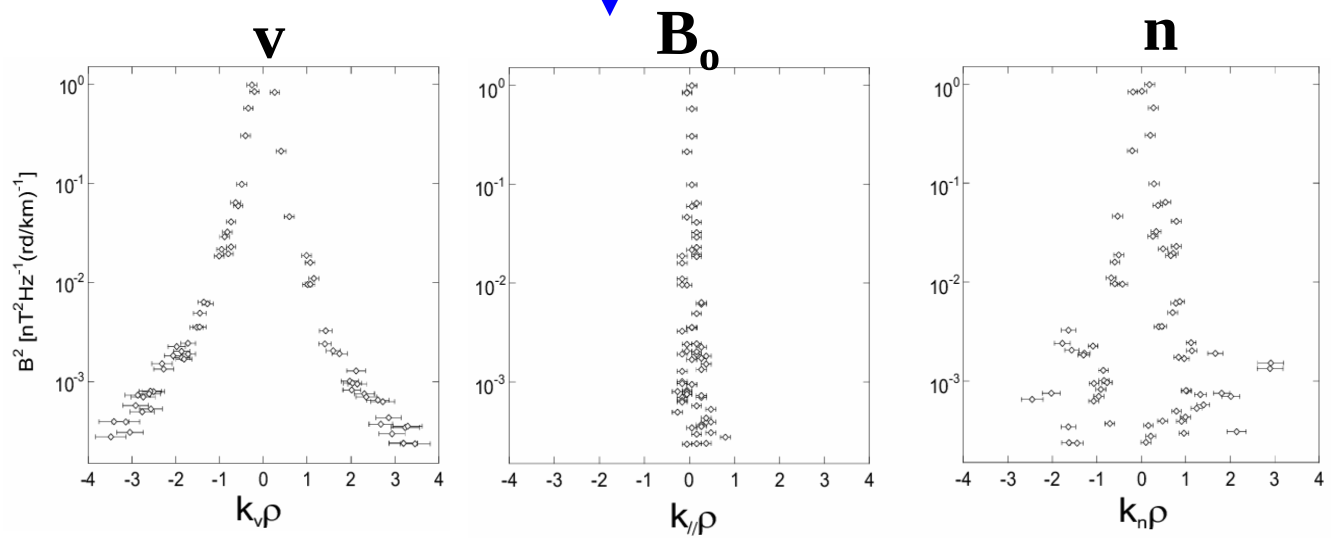
$\Rightarrow$ ***f_{max} ~ 2Hz***

Direct determination of 3-D anisotropic k-spectra





(v,n) ~ 104° (v,B_o) ~ 110° (n,B_o) ~ 81°

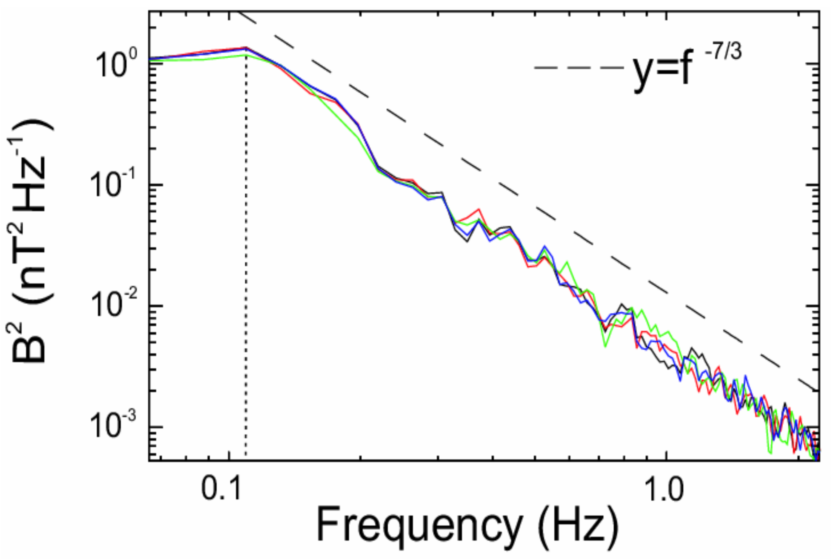


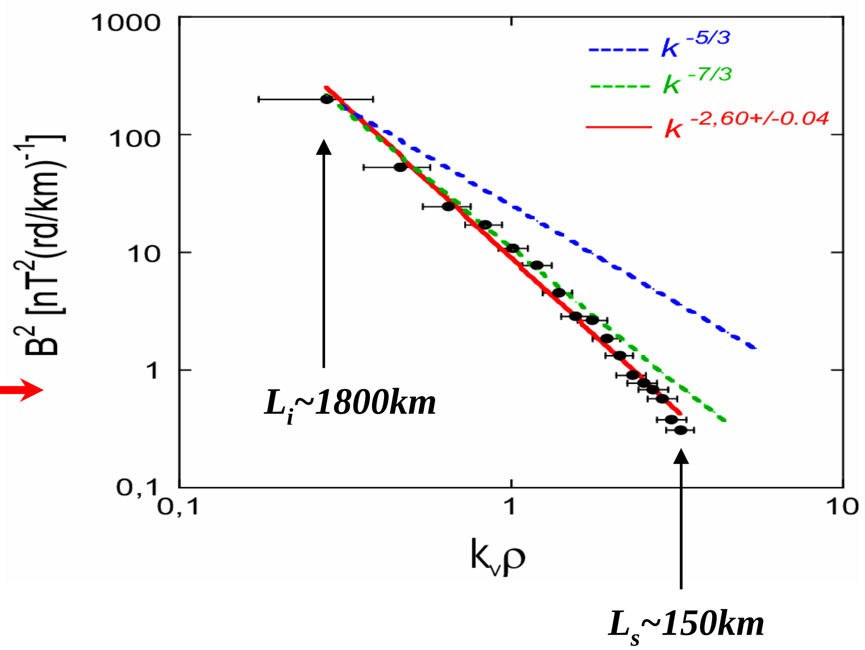
fully 3-D k-spectra: strong anistropies along B_o, the magnetopause normal n, and the flow v

Evidence of a turbulent cascade of mirror structures

A double integration: $P(\mathbf{k}) = \sum_{f_{sc}} P(f_{sc},\mathbf{k})$ and $P(k_v) = \sum_{k_n,k_{//}} P(k_v,k_n,k_{//})$

$\Rightarrow$ a hydrodynamic-like mirror mode cascade along *v*: $B^2 \sim k_v^{-8/3}$



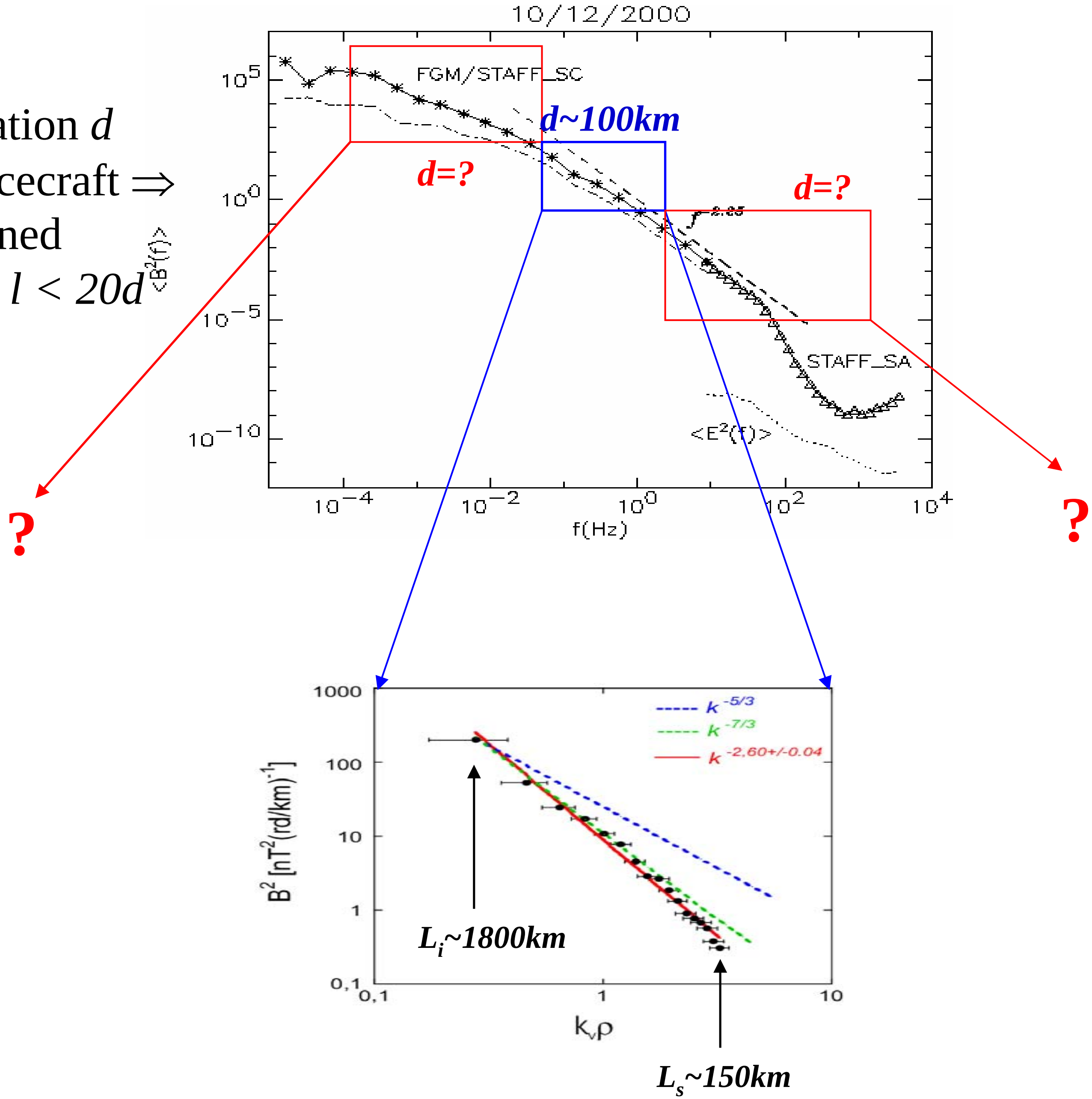


$f_{sc}^{-7/3}$ temporal signature in the satellite frame of $k_v^{-8/3}$ spatial cascade

(Sahraoui et al., PRL., 2006)

Need of multi-scale measurements

Given a separation *d* between 4 spacecraft ⇒ scales determined correctly $2d < l < 20d$



Constrainsts and requirements

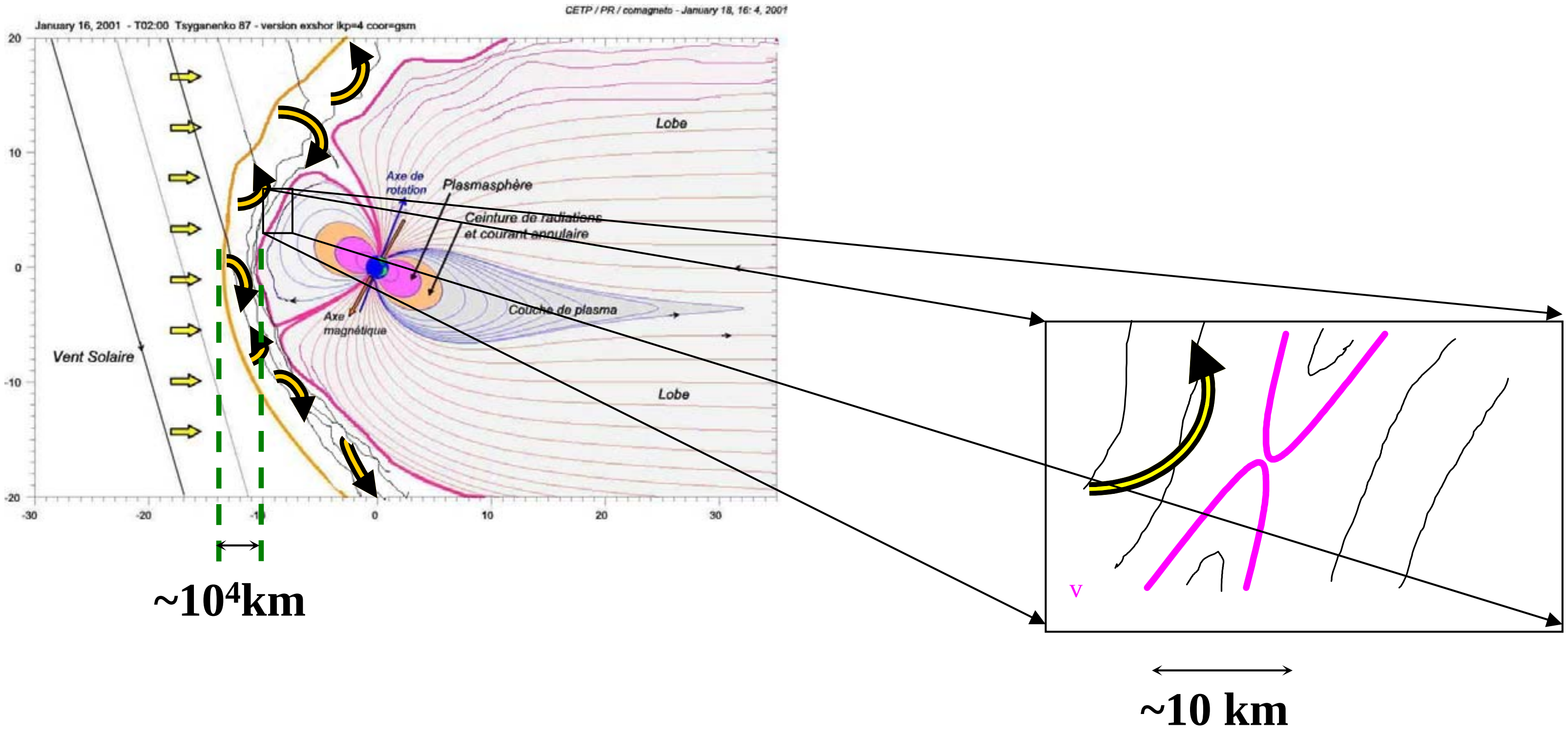
- Number of S/C: To cover inertial and dissipation scales, a range of 1:1000 ⇔ 3 scales is needed ⇔10 S/C at minimum; 12 ideal (and easier for ops').
- Distances between S/C: ideally a factor 5 to 10 between small-med-large scale (see previous viewgraph).
- InterS/C timing accuracy: 0.25msec (for 100Hz bandwith)
- 3B and 2E (3E whenever possible)
- Important to get also fast resolution particle instruments to measure fluctuations in particle energy (the total energy is an invariant).

Summary &Conclusions

- Thanks to a hierarchy of 3 sets of S/C covering 3 scales the CrossScale mission will, for the first time, provide a full characterization of a turbulent cascade. (inertial=>dissipation range) in the collisionless plasmas surrounding the Earth.

- Relation between large scale structures such as FTE's or tail flux ropes and dissipation at small scale.
- Possible relation between large scale injection of energy fluctuations from the SW and reconnection at a much smaller scale (the electron scale?, where dissipation is believed to take place)
- Role of turbulence in plasma transport.

Can ULF turbulence drive transfers across the magnetopause ?



The fluctuations necessary to drive reconnection are very small scales (*a few km*) while ULF turbulence at MP concerns much larger scales (*several 10^3 km*)

⇒Cascade process?

But, which modes? scaling laws? …